

Parsec-scale structure in galactic disk and halo, from diffuse radio polarization

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Abstract. We present multi-frequency polarization observations of the diffuse radio synchrotron background modulated by Faraday rotation. No total intensity is observed, indicating that total intensity does not vary on scales below approximately a degree. However, polarized intensity and polarization angle show abundant small-scale structure due to Faraday rotation in the warm ionized disk on small scales. The distribution of Rotation Measures enables us to estimate structure in magnetic field, weighted with electron density, in the warm ionized disk.

1 The observations

Synchrotron radiation emitted in our galaxy provides a diffuse radio background. Small-scale structure in the linearly polarized component of this radio background provides unique information about the structure in the warm Interstellar Medium (ISM) and the galactic halo on parsec scales and larger (see discovery paper [10]).

With the Westerbork Synthesis Radio Telescope (WSRT) we mapped the polarized radio background in a $7^\circ \times 9^\circ$ field centered on $(l, b) = (161, 16)^\circ$, in five frequency bands (341, 349, 355, 360, and 375 MHz) with a bandwidth of 5 MHz simultaneously, at a resolution of $\sim 4'$. No total intensity I was detected down to ~ 0.7 K, which is $\lesssim 1.5\%$ of the expected sky brightness in this region, indicating that I does not vary on scales detectable to the interferometer, i.e. below about a degree. However, linearly polarized intensity P and polarization angle ϕ show abundant small-scale structure.

1.1 Structure in polarized intensity P

There is a wide variety in topology of the structure in polarized intensity P , on several scales (Fig. 1a). The typical brightness temperature $T_{b, pol} \approx 6 - 8$ K (maximum ~ 15 K), and the maximum degree of polarization is $\sim 30\%$, with an average of $\sim 10\%$. In addition, a pattern of black narrow wiggly canals is visible (see e.g. the canal around $(\text{RA}, \text{dec}) = (92.7, 49 - 51)^\circ$), caused by beam depolarization. These canals are all exactly one synthesized beam wide and have been shown to be borders between regions of fairly constant polarization angle ϕ where the difference in ϕ is approximately 90° ($\pm n 180^\circ$, $n = 1, 2, 3 \dots$) caused by abrupt changes in Rotation Measure (RM) [6]. Hence,

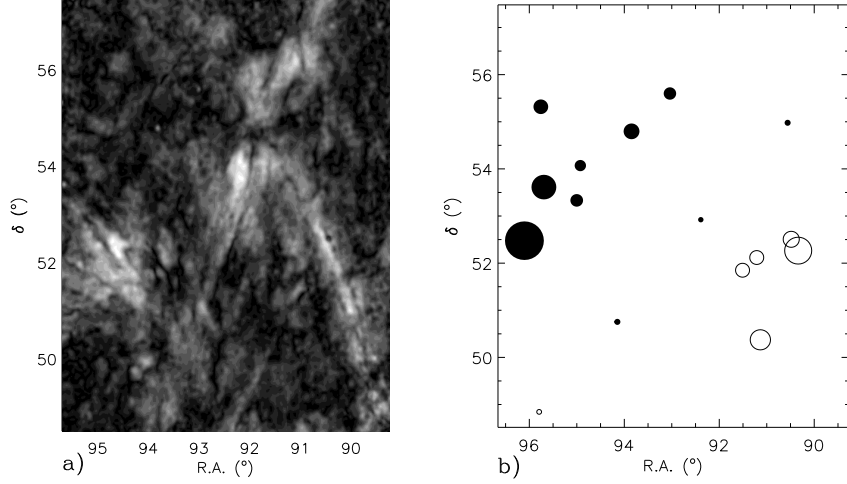


Figure 1: a) Polarized intensity map at 349 MHz at $4'$ resolution, white denotes a maximum $T_{b,pol} \approx 15$ K; b) Rotation Measures (RM's) of observed polarized extragalactic sources. The radii of the circles are scaled with magnitude of RM, where black circles denote positive RM's. Maximum (minimum) RM is 19.5 (-13.6) rad m^{-2} .

the canals reflect specific features in the angle distribution. Other angle (and RM) changes within the beam cause less or no depolarization, so that they do not leave easily visible traces in the polarized intensity distribution.

1.2 Extragalactic sources

Seventeen polarized extragalactic sources were detected at a higher resolution ($\sim 1'$), with RM's from -13.6 to 19.5 rad m^{-2} . Fig. 1b shows the RM's and positions of the sources, where the radii of the circles are proportional to RM, and white (black) circles denote negative (positive) RM's. The RM's of the extragalactic sources increase roughly in the direction of galactic latitude, indicating a galactic component to the RM's of the sources. We estimate a RM component intrinsic to the source of $\lesssim 5$ rad m^{-2} , consistent with earlier estimates [8]. The RM of the diffuse galactic radiation at the position of an extragalactic source is independent from the observed RM of the source itself (see Sect. 1.3).

1.3 Structure in Rotation Measure

The Rotation Measure of the Faraday-rotating material can be derived from $\phi(\lambda^2) \propto \text{RM} \lambda^2$ (see [7] for details and pitfalls). Fig. 2a gives a $4'$ resolution RM map (which is oversampled), whereas in Fig. 2b, RM's are smoothed over

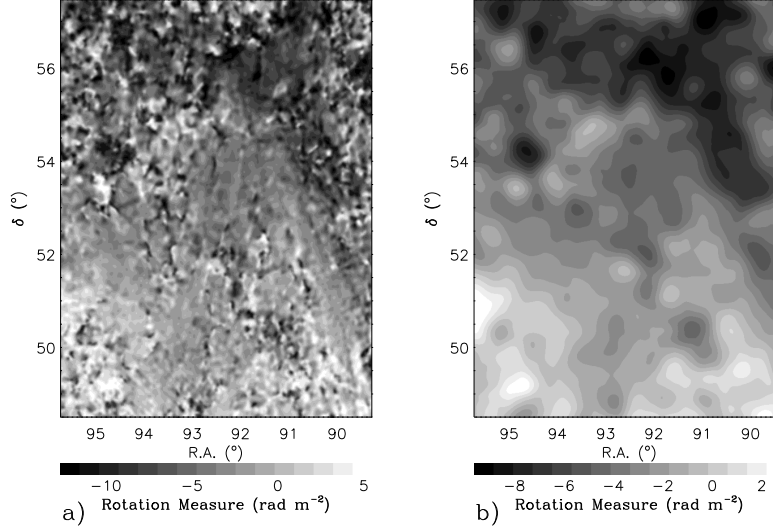


Figure 2: RM maps: a) 5 times oversampled; b) smoothed over 8 beams

8 beams ($\sim 30'$). The average RM $\approx -3.4 \text{ rad m}^{-2}$, and in general $|\text{RM}| \lesssim 10 \text{ rad m}^{-2}$. Note that the RM structure in the diffuse radiation is of the same order of magnitude but uncorrelated to the RM's of the extragalactic sources.

2 Interpretation of the observations

The galactic synchrotron radiation is emitted in a halo of relativistic electrons with a scale height $\sim 3.6 \text{ kpc}$ at the radius of the Sun (the “thick disk” in [2]). The synchrotron emissivity is strongest in the galactic plane, and decreases outwards.

Reynolds determined the exponential scale height of thermal electrons in the galaxy to be $h_e \approx 1.5 \text{ kpc}$, forming the so-called Reynolds layer [9]. Thus at several kpc above the galactic plane, the thermal electron density is very low and Faraday rotation is negligible, whereas in the Reynolds layer considerable Faraday rotation occurs.

The galactic magnetic field consists of a large-scale component, which at this longitude ($l = 161^\circ$) is almost perpendicular to the line of sight, and of a random component [3]. Therefore, B_\perp (determining the intensity of the synchrotron emission) includes the complete large-scale galactic magnetic field, whereas B_\parallel (determining Faraday rotation) is almost completely random.

The non-detection of structure in synchrotron emissivity puts constraints on the structure in relativistic electron density $n_{e,rel}$ and magnetic field perpendicular to the line of sight, B_\perp . Absence of structure in $n_{e,rel}$ and magnetic field in the halo is also observed in external galaxies, e.g. M51 [1] and M31 [4].

For total intensity I to be constant in the Reynolds layer as well, $n_{e,rel}$ must be smooth, and the large-scale magnetic field component must dominate the turbulent component. If the Reynolds layer consists of many cells with different turbulent magnetic field $B_{\perp,turb}$, some local variations in synchrotron emission could exist, which would be averaged out along the line of sight. However, a large amount of turbulent cells also decreases the degree of polarization. As we observe a high degree of polarization, the amount of possible turbulent cells is limited, and only a few K in local variations in total intensity could be erased in this way.

So the polarized component of the synchrotron emission also has little or no small-scale structure. However, Faraday rotation in the Reynolds layer varies on small scales (Fig. 2), inducing structure in polarization angle. Linearly polarized radiation emitted at different depths is Faraday-rotated by different amounts, which causes depolarization (internal Faraday dispersion [5]) on small scales, and so induces small-scale structure in P . Emission from the far side of the Reynolds layer is mostly depolarized, so the polarized emission we observe comes from the nearest part of the layer.

Therefore, the observed Rotation Measure is built up in this nearest part of the layer, and structure in RM denotes structure in B_{\parallel} in the nearest part of the layer. The observed RM in extragalactic sources, however, is built up over the entire line of sight. The gradient in RM of the sources on degree scales in Fig. 1b, roughly in the direction of galactic latitude, is not visible in the RM structure of the diffuse radiation, i.e. not dominant in the nearest part of the Reynolds layer.

Concluding, our observations of total intensity I , polarized intensity P , and Rotation Measure of diffuse radiation and extragalactic sources, impose many constraints on the possible nature of magnetic field and electron density in the warm ionized gas and in the synchrotron halo (for details and calculations, see [7]).

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